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Zero energy communities with central solar plants using liquid desiccants and local storage

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Abstract

The *zero energy community* considered here consists of tens to tens-of-thousands of residences coupled to a central solar plant that produces all the community's electrical and thermal needs. A distribution network carries fluids to meet the heating and cooling loads. Large central solar systems can significantly reduce cost of energy vs. single-family systems, and they enable economical seasonal heat storage. However, the thermal distribution system is costly. Conventional district heating/cooling systems use a water/glycol solution to deliver sensible energy. Piping is sized to meet the peak instantaneous load. A new district system introduced here differs in two key ways: i) it continuously distributes a hot liquid desiccant (LD) solution to LD-based heating and cooling equipment in each home; and ii) it uses central and local storage of both LD and heat to reduce flow rates to meet average loads. Results for piping sizes in conventional and LD thermal communities show that the LD zero energy community reduces distribution piping diameters meeting heating loads by ~5X and meeting cooling loads by ~8X for cooling, depending on climate.

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Keywords: Solar thermal; community-scale; district heating/cooling; liquid desiccants; pipe size reduction

1. Introduction

The zero energy community (ZEC) considered here consists of tens to tens-of-thousands of residences coupled to a central plant that produces all the community's electrical and thermal needs. There are three parts to such systems: the *central plant*, the thermal *distribution network*, and the *loads/buildings*. The central

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plant is presumably solar-driven; it provides electricity and heat. Solar plants usually have seasonal storage to address the obvious heating load-solar resource mismatch. The buildings can be residential or commercial, with space heating, space cooling, and water heating loads. The distribution network consists of insulated pipes carrying fluids to the loads. In a conventional system, the fluid is a freeze-resistant solution carrying ***sensible*** energy only, and the piping is sized to meet the ***peak*** heating/cooling loads for given supply and return temperatures. Large well-insulated pipes located in trenched concrete casements are typical; cost of the thermal distribution network is a dominant cost and a barrier to central systems [1]. The liquid desiccant (LD) system discussed here delivers both ***sensible and latent*** energy to local storage to meet ***average*** heating and cooling loads, significantly reducing piping size and distribution system costs.

Nomenclature

Symbols and subscripts

AC	air conditioner
bldgs	buildings
clg	space cooling
c_p	specific heat
d	pipe diameter
distr	distribution system
DHW	domestic hot water
div	diversity of loads
F	factor (for diversity and for heat loss)
HP	heat pump
htg	space heating
HVAC	heating, ventilation, and air conditioning equipment
LD	Liquid desiccant
m	mass
N	number
PV	photovoltaics
PV/T	PV/Thermal
Q	quantity of thermal energy
T	temperature or thermal-only collectors
v	average velocity of the fluid in the pipe
ZEC	zero energy community
Greek Symbols	
Δ	change in a quantity
π	pi, ratio of circumference to diameter
ρ	density
ω	mass fraction, $\omega \equiv m_{salt}/(m_{H20} + m_{salt})$

A large central solar plant provides energy at significantly lower cost vs. single-family residential systems, principally due to *economies of scale* and reduced *soft costs* (e.g., permitting, distribution, and marketing). When using sufficiently high concentration of sun (> ~500X), high-efficiency triple-layer cells with ~40% efficiency can provide more economical electrical power on roughly half the footprint vs. Si cells with 20% efficiency. With a large-scale central solar plant, economical seasonal storage is possible; seasonal stores are somewhat commonplace in Europe [1], but are rare in the U.S.

The central plant generates electrical and thermal energy, from photovoltaic (PV) and solar thermal collectors. “Waste” heat from cooling of the photovoltaics (PV/T) can be used to more than double energy output. However, there is a fundamental PV/T conflict: PV cells should operate as cool as possible to maximize their electrical production, while heat should be sufficiently hot to meet thermal loads. Si cells have a temperature coefficient giving ~0.5%/^{o}C degradation in efficiency; similarly, the GaAs temperature coefficient is ~0.2%/^{o}C. Reliability concerns limit driving the cells over 100 ^{o}C. To raise the temperature of the PV/T thermal output to 95 ^{o}C (for sensible storage) or 140 ^{o}C (for liquid desiccant regeneration) space conditioning or DHW use, thermal-only collectors are needed to boost the temperatures from the PV/T. These collectors will generally be concentrating (such as troughs), to provide sufficiently high temperatures for distribution and driving two-stage thermally-activated cooling. However, we do not discuss design of the generation system here; we simply assume the required heat or cold is provided at the desired temperatures.

The main downside of using the thermal energy from a central plant is the distribution system cost. The trunk lines for a 1000-home conventional ZEC have diameters 1-2 feet, they must be insulated, and they require deep trenching and concrete enclosures. This paper addresses distribution system costs with a new design for a ZEC based upon liquid desiccants (LD) that reduces the diameter of the piping required by ~5X and ~8X for heating and cooling, respectively. After describing the two approaches to a ZEC and discussing the assumed ZEC loads, and the postulated LD-based heating, ventilating, and air conditioning (HVAC) equipment, we quantify and compare required pipe sizing for conventional and LD-based district systems.

2. Community systems overview: conventional and proposed

Fig. 1 is a schematic of a ZEC using a conventional district system supplying both heating and cooling. The central plant supplies hot fluid to the network from the solar heat source, and cold fluids from a central chiller driven by solar heat. Large absorption chillers driven by solar heat are available. Seasonal heat storage is used to even out the solar resource/heating-load mismatch. Cold storage can also be done, charging the store from ambient cold winter air or a nearby body of water. In order to ideally meet simultaneous heating and cooling loads (domestic hot water [DHW] and space cooling in summer), four pipes are needed: separate supply/return lines for hot and cold fluids. It is possible to use two pipes only, if a seasonal changeover from hot to cold is done, with electric heating for the DHW load when in cooling mode. The PV has to be upgraded to “make up” for that added electric energy use. To avoid problems with network failures in winter, the network fluid must be freeze-resistant for most all U.S. climates. The central plant must generate and distribute fluids through pipes large enough to carry the flows needed to meet peak instantaneous loads. Each house has three heat exchangers, for the space heating and cooling, and DHW loads; the heating and cooling heat exchangers could be combined with appropriate valving. The hot side network temperature may be as high as 82 ^{o}C (180 ^{o}F) to drive convectors in each house. Outdoor temperature reset is useful to reduce tank losses. The cold side network is as low as 10 ^{o}C (50 ^{o}F).

Fig. 2 is a schematic of the new LD-based ZEC. The LD ZEC concept presented here evolved from earlier work done on a single-family LD-based zero energy home using the same LD-based HVAC [4]. LDs are typically halide salts in water, such as LiBr or $CaCl_2$. LDs have a low vapor pressure compared to saturation pressures over water, which drives the water vapor transport processes used in the LD-based HVAC. The heat from the concentrating collectors goes to either the LD regenerator or the sensible storage, depending on state of charge of LD and heat stores. A two-stage regenerator achieves a thermal coefficient of performance of ~1.2 by boiling LD at atmospheric pressure in the first stage, and using the steam to drive a second stage regenerator. A small-scale unit is under test [3]. Boiling LD requires input temperatures > ~140 ^{o}C (284 ^{o}F). Water concerns are minimized by reusing the pure water produced during regeneration. Codes will likely prohibit re-injection of this "industrial water" into the potable water system, and the reclaimed water would be used elsewhere. Then, the only water lost in the community LD system is what exits in the indirect evaporation exhaust air streams during LD-AC operation.

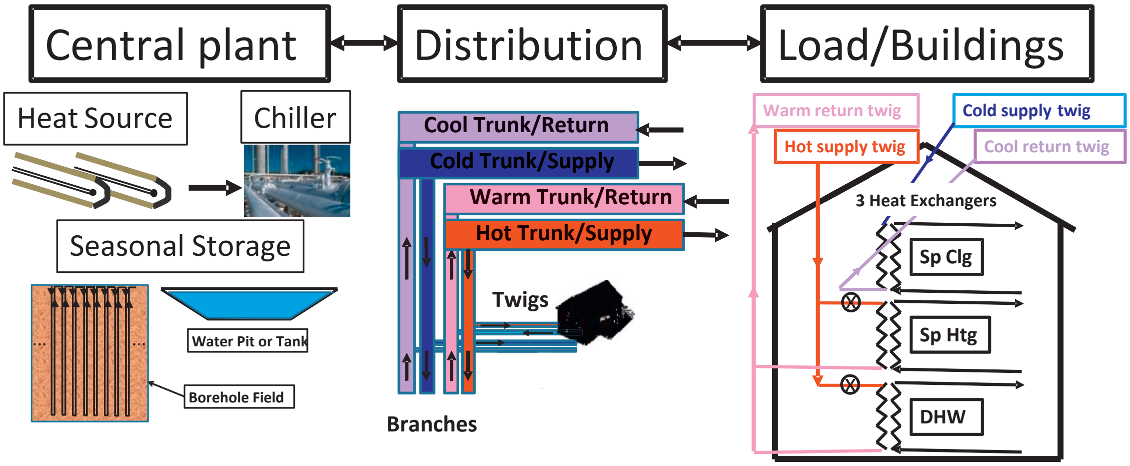

Fig. 1. A zero energy community using a four-pipe conventional district system (see text for a two-pipe alternative).

There are *two* stores at the LD central plant, as shown in Fig. 2: 1) a large LD tank, storing both strong and weak LDs; and 2) a large sensible storage, shown as a borehole field. In addition, heat is stored in each building in two local stores: 1) a small hot LD storage tank; and 2) a larger sensible store, which takes the heat supplied by the network and stores it for peak heating periods in winter. Lastly, each building uses HVAC driven by LD. If cooling/heating is very small, the air conditioner/heat pump would be eliminated, respectively. The LD heat pump can be eliminated, even in a heating climate, by using only the network sensible heat with local storage to meet heating loads. When doing so, one must upsize the central plant heat collection by ~20%, increase the LD pipe diameter, and increase the capacity of the local sensible heat store by ~2.5X.

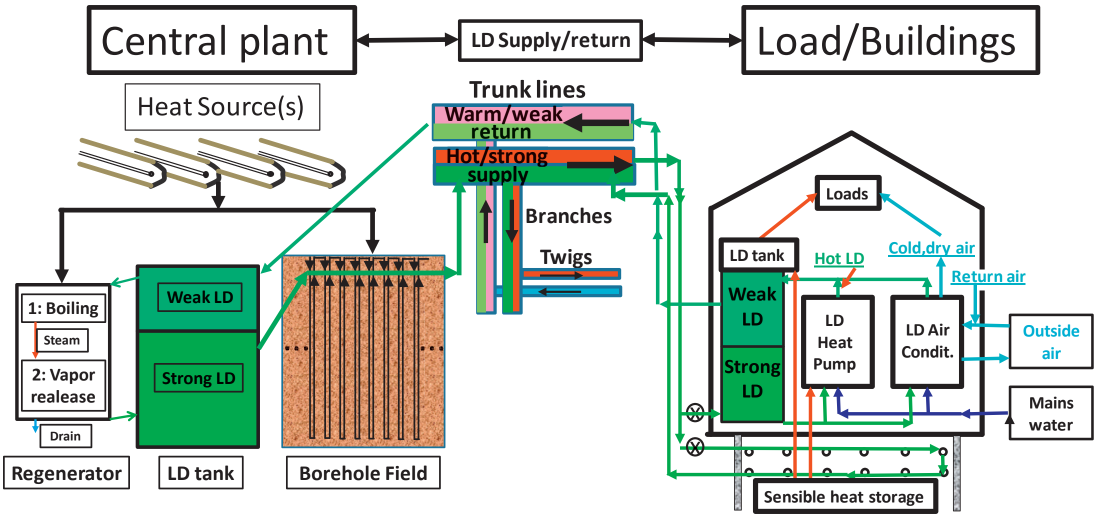

Fig. 2. An alternative zero energy community, using liquid desiccants and local storage.

3. Central plant storage

Seasonal storage is essential to utilize the plant's thermal energy for a ZEC. Large stores are generally more efficient and lower in unit energy storage cost than small stores. Figs. 1 and 2 exemplify borehole sensible heat storage. Approaches to large stores are given in Table 1. Water and earth are currently the only materials used for seasonal storage. Phase change materials have no advantage when the ΔT_{store} is large, as in seasonal stores. Thermochemical storage at ~30X water energy densities remains promising; someday suitable reactants might be identified. For the LD ZEC central plant, a second storage tank is needed for the LD heat transfer fluid. The insulated storage could be a tank or a pit store, either being lined with polymer films to resist corrosion in the tank and contain the fluid. As indicated in Fig. 2, the weak LD is stratified on top of the strong LD by buoyancy forces without a separating membrane [5].

Table 1. Some central plant seasonal storage options

Type of storage	Notes
Earth storage	Large communities
Borehole store	Deep U-tubes of HDPE; for bigger communities (top insulation only)
Aquifer flow store	Injection (summer) and extraction (winter) wells (no insulation)
Water storage	Has ~4X the volumetric heat capacity of earth
Large insulated tank(s)	Tanks can be buried; intermediate size communities
Pit store	Small to intermediate size communities
Geological caverns/mines	Large communities; depends on availability/local geology

4. Loads and local storage

For simplicity in calculating the community loads, we assume a community of 1000 identical homes. Commercial buildings and other loads would generally also be included, but we consider only residential loads here. Space heating and cooling loads change relatively slowly and can reasonably be assumed to be coincident for calculating community loads from house loads. For DHW, a 0.3 diversity factor is assumed for peak water heating loads, based on observed overlap in water usage in the "morning rush hour" [6]. A more precise literature value for DHW diversity was not sought for this study.

The loads used here are calculated from simulations done in eight cities for a three-bedroom house [7], using the Building America house simulation protocol [8]. The building used there was reasonably efficient, meeting 2009 residential building code [8]. Occupancy assumptions and other details of the simulation model and input assumptions are given in [7]. Zero energy dogma rightly dictates *efficiency first*. In zero energy design, the loads are reduced with efficiency until the point is reached where renewable generation is less expensive than available efficiency measures. At that point, the building's space conditioning loads are reduced by 50-80%, with whole house load reduced 40-60% [9]. Reductions were somewhat higher for space heating than for cooling and depend on climate. Somewhat artificially, we generate a set of heating/cooling loads by reducing the loads in [7] for heating/cooling by 70%/60%, respectively. DHW and all other uses are assumed to be unchanged from [7]. The monthly heating and cooling loads assumed are shown in Fig. 3.

Local storage at each home allows flow rates in the distribution piping to be reduced for both cooling and heating. As in Fig. 2 and Fig. 6a, a local tank of several hundred gallons stores hot LD, replenished by the network. At LD flow rates in [7], this tank stores a month of LD for the LD-AC. In the hot LD tank are two heat exchangers, for DHW and for heating loads. The tank allows for a reduced LD flow rate during summer by supplying LD to the chiller at times when the network capacity is too low to meet the local load directly. The LD tank also stores heat flows from the secondary storage and heat pump. A second local storage is used for sensible heat. The ground under the house can be used with new construction, as illustrated in Fig. 2. The thermal capacitance of under-house ground storage is large, providing sufficient capacity to bridge between summer excess and winter deficit heat. With a relatively large ground store charged continuously by circulation of fluid from the central plant/storage, flow rates from the central plant for heating can be reduced so that the total annual heat needed is delivered at a constant, low flow rate.

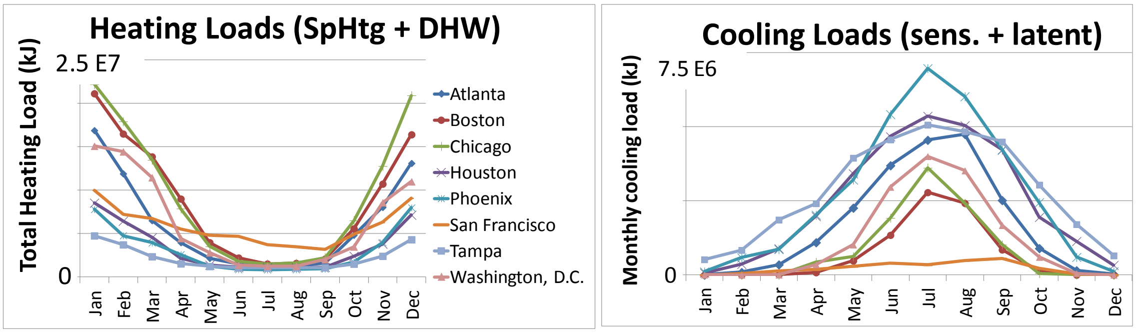

Fig. 3. Heating and cooling loads per home assumed for the zero energy community.

5. Liquid-desiccant-based HVAC

The LD-AC and LD-HP described below are the basis for using LD as the network fluid. The U.S. Department of Energy is funding work on the LD-AC, and there has been significant commercial interest in the unit described below, giving some prospect of such units entering the market within a few years. However, there is no current work on the LD-HP. Because neither LD unit is commercially available, the community concept here should be considered futuristic.

5.1 Liquid desiccant air conditioner (LD-AC)

The LD-AC is a two-stage device (Fig. 4), using de-humidification followed by indirect evaporative cooling. It is termed a *desiccant-enhanced evaporative* air conditioner (DEVAP) [11]. A numerical model of this process [12] was recently validated with experiments. As in Fig. 4a, the first stage of the DEVAP process is a dehumidifier that uses LD contained behind a membrane to remove moisture from the process air (state 1 to 1.5). Across a plastic plate from the LD, water evaporates into an exhaust airstream (3 to 4), which keeps the LD temperature and vapor pressure low. The second stage is a counterflow indirect evaporative cooler. It cools the process air (state 1.5 to 2). A portion of the cool, dry outlet air (state 2) serves as the inlet to the wet-side channels (2 to 5) opposite the process air. The DEVAP process is shown on a psychrometric chart in Figure 4b. Electricity use is limited to fans and pumps. The electricity use over a year is roughly 85% less than with a conventional vapor compression AC. DEVAP shifts cooling from electricity for the compressor to heat for the LD regenerator; total source energy savings is 40-80%, depending on climate humidity [11].

5.2 Liquid desiccant heat pump

In the LD-HP, an LD flow is separated from a counter-flowing water stream with membranes that pass water vapor to the LD. The released heat raises the LD outlet temperature above the water inlet temperature (ΔT_{lift}). The membranes are separated by a narrow air gap (Fig. 5a) which improves performance by reducing sensible heat loss between the hot LD and cool water. Prototypes of this HP were built using two sets of rows of hollow fiber membranes, with the space between these rows acting as the air gap [13]. The HP temperature lift ΔT_{lift} depends on source temperature and LD concentration, as shown in Fig. 5b. When (T_{set}-T_{amb}) < ΔT_{lift}, the HP can produce energy to meet DHW and space heating loads during that period. This process allows more of the network heat to go into the local long-term storage, but it uses more LD and regeneration heat.

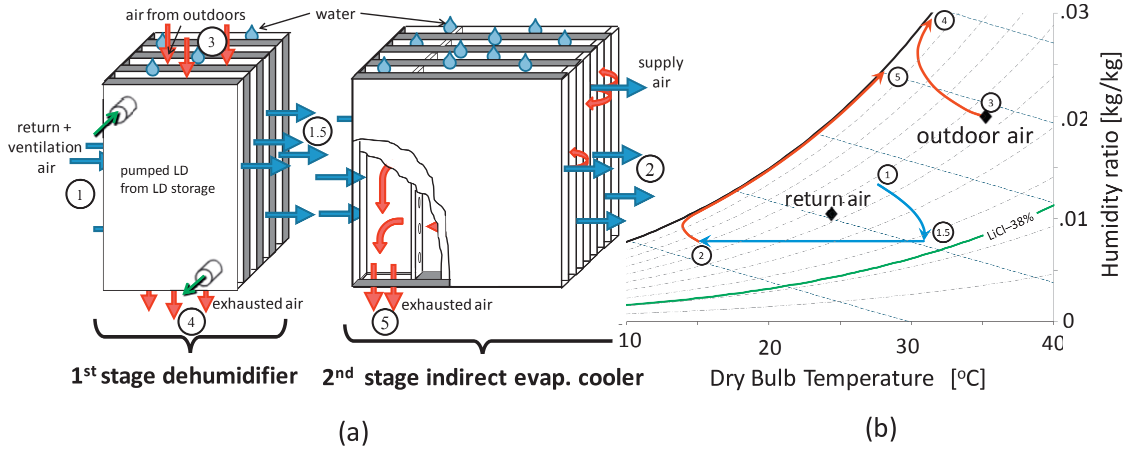

Fig. 4. Liquid desiccant air conditioner: (a) schematic drawing; (b) process on a pyschrometric chart.

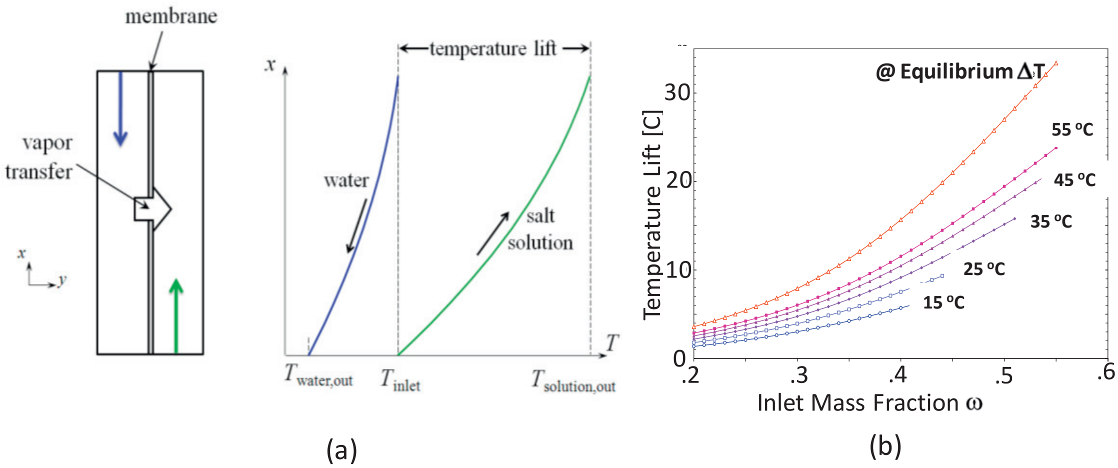

Fig. 5. LD heat pump: a) schematic (left) and temperatures (right) in fluids; b) temperature lift as function of the inlet mass fraction, for five inlet temperatures; the theoretical maximum temperature lift is also shown.

5.3 Modes of heating the liquid desiccant tank

The DHW and heating loads are met using (polymer) heat exchangers in the top of the LD storage, as in Fig. 6a. The storage is kept hot enough to meet loads by the local sensible storage or by the HP. Fig. 6 also shows three modes of charging the LD tank. It is charged off ambient air (Fig. 6d), when possible (T_{amb} > ~27 °C (80 °F)). When storage is hot enough, the tank is charged directly from the store, as in Fig. 6b. When the storage is below the temperature to directly meet the loads (~50 °C), the HP uses the storage (Fig. 6c) if (T_{amb} < 80 °F).

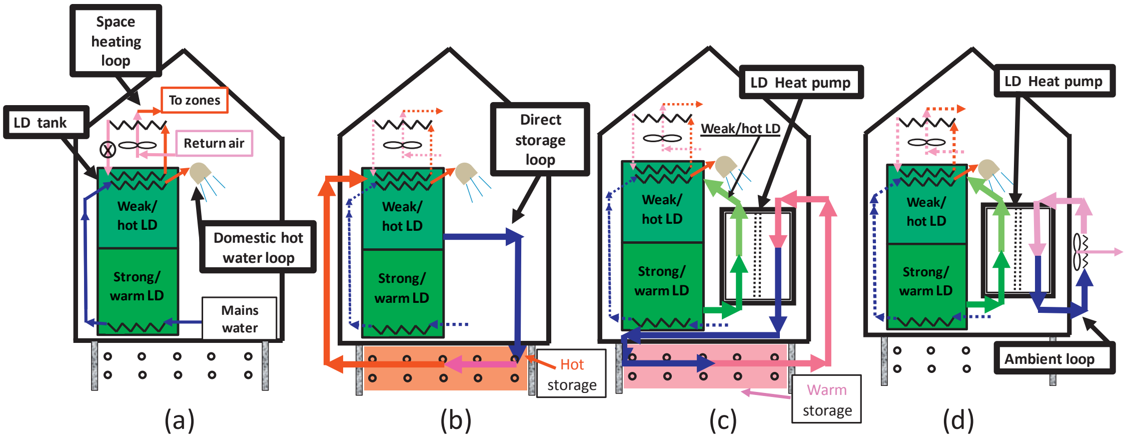

Fig. 6. The LD tank is a heating load center: (a) LD tank and heating loops; and (b)-(d) three heat sources and charging modes for the LD tank: (b) hot storage; (c) HP + warm storage; and (d) HP + warm ambient air.

6. Distribution network pipe diameters for conventional and LD district systems

Conventional system. The pipe diameter of the conventional network is set by the constraint to meet instantaneous peak loads. With diversity for DHW loads and no diversity for space heating loads and estimating a loss factor (F_{loss} , set to 1.10 here) to roughly account for piping losses, we have:

$$\dot{m}_{pipes,max} c_p \Delta T = F_{loss} \dot{Q}_{total,peak} = \sum_{i=1}^{Ntypes} (\dot{Q}_{i,SpaceHtg,peak} + F_{DHW,divers} \dot{Q}_{i,DHW,peak}) \quad (1)$$

The maximum flow rate, maximum velocity in the pipe, and pipe diameter are related as in Eqn. 2:

$$\dot{m}_{pipes,max} = \rho (\frac{\pi d_{max}^2}{4}) v_{pipe,max} \quad (2)$$

Maximum v_{pipe} is ~5 ft/sec (1.5 m/sec), to limit erosion [14]. The temperatures across the supply to return are set from practical considerations, such as the size of the building heat exchangers and avoidance of condensation. Table 2 lists supply/return temperatures used to calculate the ΔT_{distr}. The diameter is computed for maximum heating (DHW + space heating) loads and for maximum cooling loads.

The diameter of the main trunk in a conventional system is obtained by substituting Eqn. 2 into Eqn. 1 and solving for the pipe diameter:

$$d_{pipe} = \sqrt{4 F_{loss} \dot{Q}_{total,peak} / (\pi \rho c_p v_{pipe,max} \Delta T_{network})} \quad (3)$$

LD system. The LD flow rate for cooling is set by simulated DEVAP demand. Given the required LD mass flow- averaged over a time period Δt (about a month for a 200 gal LD tank, given max LD flow rates in [7])- the size of pipe carrying the LD for cooling is

$$d_{LD-pipe,clg} = \sqrt{4 \dot{m}_{LD,\Delta t-avg} / (\pi \rho_{LD} v_{max})} \quad (4)$$

Table 2. Temperatures of supply and return pipes

Pipe	Mode	
	Heating	Cooling
Supply	180 °F (82 °C)	55 °F (13 °C)
Return	130 °F (54 °C)	65 °F (18 °C)

To model storage and interaction with heat pump operation, it is necessary to make expeditious simplifying assumptions. The storage is assumed adequately large to store the heat- delivered all year by the hot LD distribution- for use in winter. We multiple annual heating loads by 1.4 to account for storage heat losses. We estimate that the LD-HP uses ambient heat to meet 20% of the space heating load and 40% of the DHW load. With these adjusted loads, Eqn. 3 is used to size the LD pipe, using LD properties rather than glycol properties.

Calculated pipe diameters are shown in Fig. 7a. For the conventional ZEC, the pipe sizes are between 1 and 1.5 feet for the eight cities. For the LD zero energy community, it can be seen that the pipes vary between 0.08 feet and 0.18 feet for cooling, and between 0.15 feet and 0.35 feet for heating. Two cases for heating are done, with and without the LD-HP. The LD-HP reduces the diameter about 15%, and it significantly reduces the local sensible heat storage, by about 2.5X vs. no HP. The LD-HP allows one to more than double the temperature change in the storage while still meeting the heating loads, as in [4]. It can be seen that the LD ZEC pipes are much smaller than those of the conventional ZEC. The pipe size reduction for cooling averages ~8X, and for heating it is ~5X, with diameter ratios for the eight cities shown in Fig. 7b. If the community has both heating and cooling loads, the result for LD heating sets the LD pipe diameters. The LD cooling diameter approaches the LD heating diameter in the hot climates of Houston, Phoenix, and Tampa.

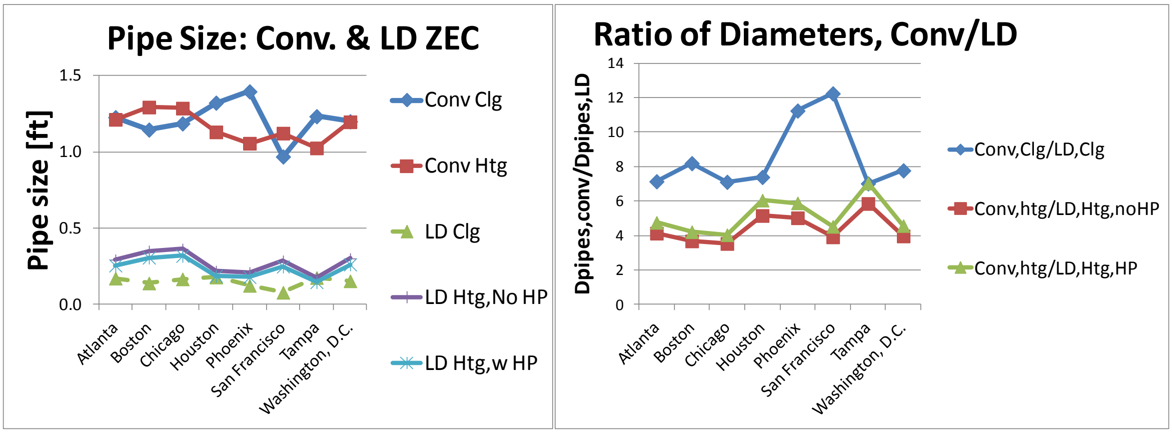

Fig. 7. Pipe sizes for conventional and LD zero energy communities: (a) pipe diameters; (b) ratio of sizes for heating and cooling.

7. Conclusions

A new type of district heating and cooling system for a ZEC has been introduced, based upon distribution of hot liquid desiccant (LD) fluid, LD-based HVAC in each home, and local storage. The central plant has renewable generation of electricity and heat, and has a central LD storage tank and a seasonal heat storage, such as a borehole field for larger communities. Hot LD is distributed in the network 365/24, charging an in-home LD storage tank and a sensible storage. There is an LD-HP and an LD-AC in each building, meeting heating and cooling needs. Each building has an LD tank of several hundred gallons, and a larger sensible heat store. The LD district system shows benefits compared to a conventional district system using heated/cooled fluids. The LD system is a two-pipe system, whereas the conventional ZEC is either four-pipe, or two-pipe with seasonal changeover and electric water heating when in cooling mode. Pipe sizes have been computed for both communities. The LD pipes are smaller than in the conventional community by ~5X and ~8X for heating and cooling, respectively. For a 1000-home community, the LD pipes are ~3 inches in diameter for a 1000 home community, depending on the climate. The small size will make the distribution pipe less costly. It may be amenable to "ditch-witching", as opposed to trenching and cement casements, thereby radically lowering LD system distribution costs.

Acknowledgements

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